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EFFECT OF INSOLATION BOUNDARY CONDITIONS ON TYPE B PACKAGE INTERNAL TEMPERATURES

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Abstract:

The prescription of the initial conditions and the final conditions for a thermal accident for Type B packages are different for differing regulations. This paper presents an analytical method for estimating the effect of the boundary conditions on post-fire peak internal package temperatures. Results are given for several boundary conditions for a Type B drum-type package.

Introduction:

The prescription of the initial conditions and the final conditions for a thermal accident for Type B packages are different for each of the regulations. The regulations each prescribe an environment temperature of 38°C. The prescriptions differ on the application of the insulation during the initial conditions and the final (post fire) conditions. The prescriptions for the application of insulation for the various regulations are shown in the Table below.

<u>Regulation:</u>	<u>Initial Conditions:</u>	<u>Final Conditions:</u>
10 CFR 71 ¹	No insulation	No insulation
IAEA Safety Series 6 ²	No insulation	Insulation
IAEA TS-R-1 ³	Insulation	Insulation

The peak temperatures in the package will occur during the cool down following a fire. An analytical method for estimating the effects on the peak temperature and time of occurrence of the peak temperature for the application of insulation to the boundary conditions is given below.

Motivation:

The boundary conditions for the analysis of a package initially assumed that the initial conditions of the package prior to a 10 CFR 71¹ hypothetical accident condition (HAC)

included insolation on the package in a 38°C environment. The post-fire boundary condition including cooling to a 38°C environment, without insolation.

Consideration of the effects of including insolation during the post-fire cool-down was requested on the temperature of the containment vessel seals, and has been investigated. The results of the effect of insolation on the temperature of the package during the post-fire cool-down are estimated below.

Analysis:

The maximum temperatures of the internal components of a package will occur after cessation of the 30-minute, 800°C fire. To estimate these temperature-time conditions, the analysis will assume a step temperature increase to the regulatory fire temperature of 800°C at the surface of a semi-infinite solid initially at a uniform steady surface temperature. The steady surface temperature is determined from a heat balance between the insolation and content decay heat flux on the surface of the package to the environment at 38°C.

The temporal temperature at a point within a semi-infinite surface caused by a step increase in the surface temperature, followed, after a specified time, by a step decrease in surface temperature is given by^{4,5}

$$(X(x,t) - 1)/(X_f - 1) = \text{erfc}[(x^2/(4\alpha t))^{1/2}] + \{(X_{pf} - X_f)/(X_f - 1)\} \text{erfc}[(x^2/(4\alpha(t - t_f)))^{1/2}]$$

where $X(x,t) = T(x,t)/T_o$; $X_f = T_f/T_o$; $X_{pf} = T_{pf}/T_o$

T_o = initial temperature

T_f = fire temperature applied at time $t = 0$

T_{pf} = surface temperature following cessation of fire at time $t = t_f$.

t = time after initiation of the fire, seconds

t_f = time duration of the fire, seconds

x = distance from the surface in the semi-infinite solid

α = thermal diffusivity of the semi-infinite solid material = $k/(\rho c_p)$, m^2/s

k = thermal conductivity of the semi-infinite solid material, $W/m-K$

ρ = density of the semi-infinite solid material, kg/m^3

c_p = specific heat of the semi-infinite solid material, $J/kg-K$.

Recasting the above equation in dimensionless units,

$$(X(x,t) - 1)/(X_f - 1) = \operatorname{erfc}[(\xi/\tau)^{1/2}] + \{(X_{pf} - X_f)/(X_f - 1)\} \operatorname{erfc}[(\xi/(\tau - 1))^{1/2}]$$

where $\xi = x^2/(4\alpha t_f)$

$$\tau = (t/t_f) > 1.$$

The temperature at a location x is a maximum at a dimensionless time τ_{\max} that satisfies

$$\tau_{\max}^{-3/2} \exp[-\xi/\tau_{\max}] = \{(X_{pf} - X_f)/(X_f - 1)\} [\tau_{\max} - 1]^{-3/2} \exp[-\xi/(\tau_{\max} - 1)] \quad (1)$$

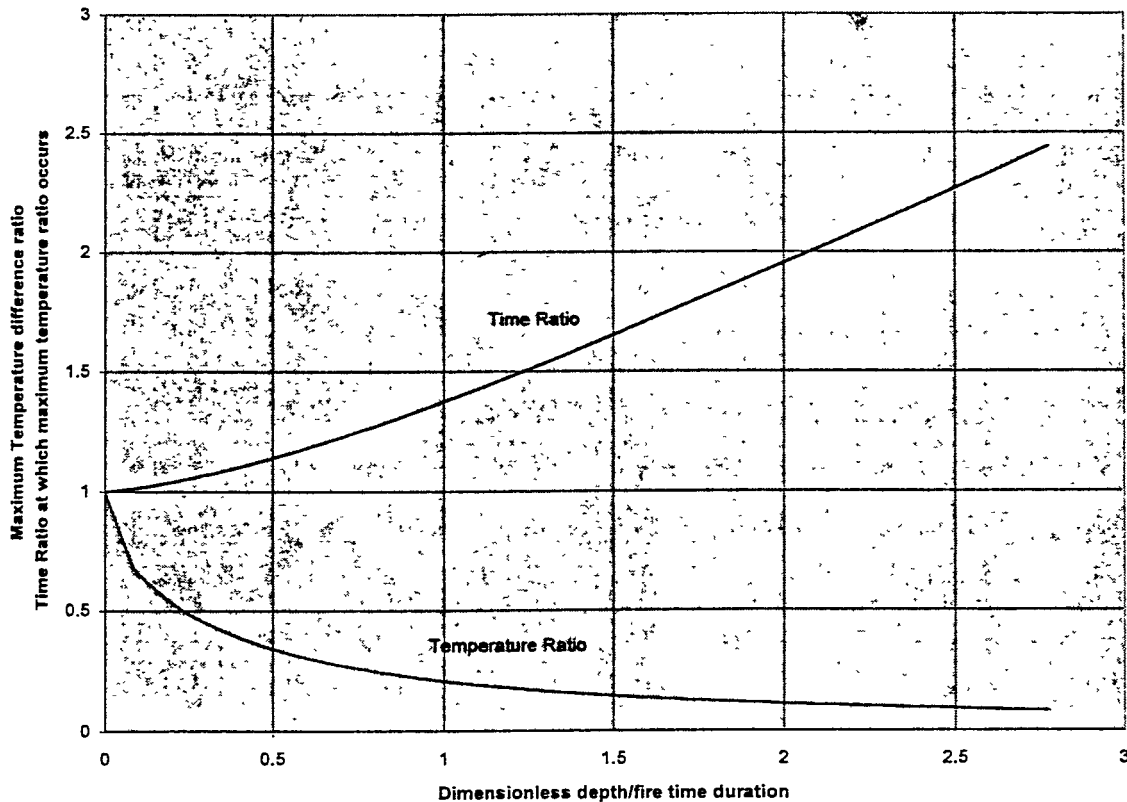
The maximum temperature $T(x, \tau_{\max})$ is found from the definition of $X(x, \tau_{\max})$, and

$$(X(x, \tau_{\max}) - 1)/(X_f - 1) = \operatorname{erfc}[(\xi/\tau_{\max})^{1/2}] + \{(X_{pf} - X_f)/(X_f - 1)\} \operatorname{erfc}[(\xi/(\tau_{\max} - 1))^{1/2}] \quad (2)$$

For the 10 CFR 71 and IAEA TS-R-1 boundary conditions, where the initial and final (post fire) boundary conditions are identical,

$$\{(X_{pf} - X_f)/(X_f - 1)\} = -1.$$

For this case, considered by Shah⁵, the ratio of the time τ_{\max} at which the maximum



temperature ratio $X(x, \tau_{\max})$ occurs and the ratio of the maximum temperature difference to the fire temperature difference $(X(x, \tau_{\max}) - 1)/(X_f - 1)$ occurs for a given $\xi = x^2/(4\alpha\tau_f)$ is shown in the figure above.

For the semi-infinite surface the initial and final surface temperatures T_o (and hence the initial interior temperatures) are determined from the following heat balance at the boundary:

$$\begin{aligned}\Phi_{\text{insolation}} + \Phi_{\text{contents}} &= \Phi_{\text{convection}} + \Phi_{\text{radiation}} \\ &= 1.24 (T_o - T_e)^{4/3} + \sigma\epsilon(T_o^4 - T_e^4) \quad (3)\end{aligned}$$

where $\Phi_{\text{insolation}} \equiv$ insolation flux, watts/m² [386 watts/m²]

$\Phi_{\text{contents}} \equiv$ content heat generation flux, watts/m²

$\Phi_{\text{convection}} \equiv$ convection flux to the environment = $1.24 (T_s - T_e)^{4/3}$, watts/m²

$\Phi_{\text{radiation}} \equiv$ radiation flux to the environment = $\sigma\epsilon(T_s^4 - T_e^4)$, watts/m²

T_o = surface temperature, K

T_e = environment temperature, K [311 K (38°C)]

σ = Steffman-Boltzman constant = 5.67×10^{-8} watts/m²K⁴

ϵ = surface emissivity

The correlation for natural convection is for air at atmospheric pressure and near room temperature and a turbulent boundary layer⁶.

For a typical drum-type package for the shipment of radioactive material, the surface content heat generation rate heat flux is typically about 25 watts/m². Thus the insolation heat flux is almost 20 times larger than the surface heat flux from the content heat generation rate. For a package surface emissivity of 0.4, the initial temperature of the semi-infinite body is 362 K (89°C) for the case with insolation, and 316.1 K (43.1°C) in the shade (without insolation).

For a cane fiberboard material (ASTM C-208), representative thermal property values⁷ of

k = thermal conductivity = 0.065 W/m-K

ρ = density = 297 kg/m³

c_p = specific heat 2046 J/kg-K.

result in

$$\alpha = \text{thermal diffusivity} = k/(\rho c_p) = 10^{-7} \text{ m}^2/\text{s}$$

For a point x located 0.1 m from the surface, typical of the location of the containment seals, and a fire duration t_f of 1800 seconds,

$$\xi = x^2/(4\alpha t_f) = 13.89$$

Four cases are considered in the Table below. These cases include the three regulatory cases of 10 CFR 71, IAEA Safety Series 6, and IAEA TS-R-1. The dimensionless time τ at which the maximum temperature occurs, from Equation (1) above, and the dimensionless temperature $X(x, \tau_{\max})$, from Equation (2) above are shown for each case:

Case		Initial Insolation	Post-fire Insolation	$\{(X_{pr} - X_f)/(X_f - 1)\}$	τ	$X(x, \tau_{\max})$
1	[IAEA ST-2]	Yes	Yes	-1.	9.785	1.0323
2	[10 CFR 71]	No	No	-1.	9.785	1.0394
3	[IAEA SS.6]	No	Yes	-0.939	∞	1.1452
4		Yes	No	-1.065	7.653	1.0305

The time in seconds/hours and the maximum temperature increase above the initial surface temperature in $^{\circ}\text{C}$ are shown below at a position 0.1 m from the surface:

Case	time (seconds/hours)	T_o ($^{\circ}\text{C}$)	$T(x, t_{\max})$ ($^{\circ}\text{C}$)	$T(x, t_{\max}) - T_o$ ($^{\circ}\text{C}$)
1	17,600/4.9	89	101.7	11.7
2	17,600/4.9	43.1	55.6	12.5
3	∞	43.1	89	45.9
4	13,800/3.8	89	100	11.0

The maximum temperature difference between Case 1 and Case 4 for the initial condition with insolation and the final condition with and without insolation is 0.7°C . For Case 3 for the initial condition without insolation and the final condition with insolation, the maximum temperature at a depth of 0.1-m in the cane fiberboard material is identical to the initial temperature if insolation were applied.

Discussion:

In general, for drum-type packages, the surface heat flux from the content decay-heat generation rate is small relative to that from insolation. Thus, as for Case 3 above, for the initial condition without insolation and the final condition with insolation, the maximum temperature at a location deep within an well-insulated package is identical to the final steady state temperature with insolation.

The effect of charring the outer layer of the cane fiberboard may change the value of the maximum temperature deep within the fiberboard. Part of the "latent heat" from the evaporation of the moisture content of the fiberboard as well as the gases produced by the formation of the char will escape from the fiberboard surface, reducing the heat from the fire conducted deeper into the fiberboard. However, some of the moisture and gases will diffuse into the cooler interior of the fiberboard and condense. This mass-transfer will thus increase the effective thermal conductivity of the uncharred fiberboard.

The char region will have a lower density and specific heat than the uncharred fiberboard caused by the loss of moisture and decomposition of the fiberboard. The effective thermal conductivity of the charred fiberboard is greater than that of the uncharred fiberboard⁸. Speculatively, these effects may enhance the rate of post-fire cool-down of the package.

The boundary conditions used in the above analysis assumed step temperature changes on the cane fiberboard surface. The actual boundary conditions include the radiation and convection heat flux from the "fire" to the package surface. Because the drum containing the cane fiberboard is fabricated from 16 gauge metal sheet, the rate of temperature increase is very large, and the drum material temperature increases to the fire temperature almost instantaneously, with a time constant of about 35 seconds. For the post-fire cool down, the time constant of the drum material is about 1320 seconds (22 minutes), which is short relative to the time for the maximum temperature to occur at a position 0.1 m from the cane fiberboard surface. The unquantified effects of the response of the drum to the fire and post-fire conditions will result in a slight increase in the maximum temperature at 0.1 m from the cane fiberboard surface, with the maximum temperature occurring at a later time than predicted.

A similar type analysis for an infinitely long circular cylinder is given by Shah⁵. Shah also gives approximations of the internal temperature in the cylinder for the inclusion of the content decay heat generation rate.

Conclusion:

For the example given, the maximum temperature increase above the initial temperature at a point 0.1-m deep in cane fiberboard caused by a 30-minute, 800°C fire with both pre-fire and post-fire insolation is 11.7 °C that occurs about 4.9 hours following the initiation of the fire. For the case with pre-fire insolation and without post-fire insolation, the maximum temperature increase above the initial temperature is 11°C that occurs about 3.8 hours following the initiation of the fire. Thus the effect of including the post-fire insolation results about a 1°C temperature increase relative to that of excluding the post-fire insolation.

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